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Continuous improvement of concrete properties using recycled cardboard ash: A sustainable alternative to cement

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Abstract: The use of alternative materials in construction is a growing trend aimed at reducing the environmental impact of cement production. This study evaluated the effect of cardboard ash as a partial cement substitute on the properties of concrete. An experimental methodology was used with 2.5%, 5% and 7.5% additions of cardboard ash. The results indicated that concrete with 5% cardboard ash reduced the absorption speed to 0.229 mm at 831.38 s^½ compared to the reference concrete. In addition, an improvement in mechanical strength was observed, with increases of 15.10%, 16.99% and 18.41% in compressive strength, and 13.76%, 19.63% and 27.33% in flexural strength, highlighting the potential of cardboard ash to optimize concrete properties. These results were evaluated according to ASTM standards. In conclusion, the use of cardboard ash in concrete production contributes significantly to sustainability by reducing CO_2 emissions, making this material a greener and more environmentally efficient option.

Keywords: Carbon footprint, construction engineering, physical-mechanical resistance, sustainability.

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1. Introduction

Metals are the most widely used materials in armour design. Climate change and the increase in greenhouse gas emissions, particularly carbon dioxide (CO_2), represent an urgent global challenge. There is a broad consensus on the need to reduce these emissions immediately (Rose, 2021). CO_2, which is a significant greenhouse gas, has reached unprecedented levels in the atmosphere, surpassing 400 parts per million (Cubero & Doménech, 2021).

According to the International Energy Agency (IEA), global CO_2 emissions related to energy increased by 1.1% in 2023, adding 410 million tons of additional CO_2. Despite global economic growth of 3% in the same year, the increase in CO_2 emissions was slower, indicating some progress. However, emissions still reached a record 37.4 gigatons, reflecting the lack of necessary reductions to meet the climate targets of the Paris Agreement (IEA, 2023). This highlights the critical need for emission reductions in key sectors, including construction, where innovation can play a crucial role.

On the other hand, the synthesis report of the Intergovernmental Panel on Climate Change (IPCC), cited by the United Nations (2022), highlights that human activity has been the primary cause of global warming, with an average increase of 1.1 °C since the pre-industrial era. This phenomenon has been driven by the burning of fossil fuels, unsustainable resource use, and consumption patterns that exceed ecological limits. The report urges profound changes across all economic sectors, not only to mitigate climate change, but also to achieve sustainable development and net-zero carbon emissions in the future.

The construction sector is one of the largest contributors to global greenhouse gas emissions, accounting for at least 37% of the total (Esty, 2023). This is mainly due to the intensive use of materials like cement, steel, and aluminum throughout the global supply chain. Among these, the cement industry stands out for its high pollution levels, making it a key target for emission reduction strategies United Nations Environment ([UNEP], 2023).

Given this, the use of recycled cardboard ash as a partial substitute for cement presents a viable strategy to reduce these emissions. This material, derived from industrial waste, provides a sustainable alternative by reducing cement consumption and promoting efficient waste management. This approach significantly reduces the environmental impact of the construction sector while improving the physical and mechanical properties of concrete.

Additionally, the concrete industry in Peru faces challenges due to its diverse geography and climatic conditions, which require adjustments in concrete formulation to ensure durability and structural efficiency. The use of additives has been key to adapting concrete mixes to these different environments, optimizing their properties according to the specific needs of each region and type of construction (Huaquisto & Belizario, 2018). In this context, the search for partial cement substitutes, such as industrial ashes, emerges as a viable and sustainable solution.

Recent studies have shown considerable improvements when using different types of ash as a partial substitute for cement in concrete. For example, Islam et al. (2024) demonstrated that the addition of 10% fly ash resulted in a 7.9% increase in compressive strength and 14.2% in tensile strength after 28 days, compared to the control concrete. Similarly, Saraswat et al. (2023) used coconut shell ash, registering increases in the compressive strength of concrete by 21.86% and 16.41%, as well as improvements in flexural strength by 10.76% and 5.90% at 7 and 28 days, respectively. These studies reinforce the relevance of investigating new sources of ash, such as recycled cardboard, which could offer similar advantages.

Sharma (2023) investigated the addition of wood ash (WA) and waste foundry sand (WFS) to concrete. The results showed that by replacing 10% of WA and WFS, compressive strength increased by 14.8%, and flexural strength by 6.7% after 28 days. Water absorption in samples with WA and WFS was 2.1%, 1.5%, and 1.2%, compared to control samples that showed an absorption speed of 2.6%, 2.5%, and 1.8%, respectively. These studies reinforce the relevance of investigating new ash sources, such as recycled cardboard, which offer similar advantages.

Similarly, León et al. (2020) achieved a reduction in cement content by using a mix design with more aggregates, obtaining a water absorption speed of 4.8×10^5 m/s^½ after 28 days. This result yielded an effective porosity of 5.52%, complying with the Colombian Standard (NC) 120:2018, which states that reinforced concrete in extremely aggressive environments should not exceed 10% effective porosity. These results indicate that incorporating additional materials improves concrete durability, a relevant aspect to consider when partially replacing cement with recycled ashes.

Finally, Carpio and Muñiz (2024) conducted a study in which they replaced cement with mixes containing between 1.5% and 6.0% of cardboard ash and between 1.0% and 4.0% of recycled ceramics. The results showed a water absorption speed of 0.061 g/s and a permeability of 297.09 g/m². After 28 days, maximum strength was 323.34 kg/cm² in compression and 35.76 kg/cm² in flexion. They concluded that the addition of ashes improves concrete properties when used in controlled amounts; however, excessive use or inappropriate proportions can lead to a decrease in the material's strength. These findings provide a solid foundation for future research on using recycled ashes as a partial substitute for cement.

These studies clearly suggest that ashes from various sources have positive effects on concrete's compressive strength due to the natural reaction between ashes and calcium hydroxide during cement hydration, resulting in a denser and stronger concrete matrix. Additionally, ashes improve flexural strength by providing a uniform distribution of pores and a more compact microstructure, enhancing concrete's ability to distribute internal stresses during dynamic or impact loads. These findings emphasize the importance of continuing to explore alternative ash sources, such as recycled cardboard, to sustainably improve concrete's mechanical properties.

Recognizing this reality, the initiative to collaborate with the cement sector, one of the largest emitters of greenhouse gases, arises with the objective of mitigating or transforming its carbon footprint (Sobrevilla, 2016). It is crucial that incentives for decarbonization empower all involved parties equitably, from producers to consumers, including both formal and informal construction sectors (UNEP, 2023).

This growing need has driven the search for sustainable and environmentally friendly alternatives in cement production. One of the most promising solutions is the use of alternative materials, such as recycled cardboard ash, to partially replace cement in concrete mixes. These ashes improve the physical and mechanical properties of concrete, while providing a sustainable solution for industrial waste management. The incorporation of this byproduct in concrete production promotes a circular economy, benefiting both the environment and the construction sector. This practice aligns with global efforts to reduce carbon emissions and can be adapted to meet the specific needs of various construction environments.

This study is aligned with the Sustainable Development Goals (SDGs), specifically SDGs 9, 11, 12, and 13. SDG 9 promotes resilient and sustainable infrastructure through innovation, such as the use of recycled cardboard ash instead of cement. SDG 11 supports sustainable construction and the reduction of environmental impact in cities. SDG 12 encourages the efficient use of resources and the recycling of materials to improve sustainability in construction. Finally, SDG 13 aims to reduce CO_2 emissions by using alternatives to cement, such as recycled cardboard ash.

The primary objective of this article is to analyze the effect of recycled cardboard ash on the properties of concrete when used as a partial cement replacement. This study is significant because it explores how this alternative can contribute to the development of more sustainable and environmentally friendly construction. The findings of this research hold the potential to transform the management and production of concrete in the industry, as well as its use in various construction environments.

In this context, this study hypothesizes that the partial substitution of cement with recycled cardboard ash will improve the mechanical properties of concrete while also reducing its carbon footprint, particularly in aggressive environmental conditions.

2. Materials and methods

2.1. Experimental design

This study adopted a quantitative methodological approach, using a quasi-experimental design to evaluate the impact of replacing cement with cardboard ash. The experimental procedure was carried out in several stages: (1) preparation of test specimens, (2) incorporation of varying percentages of cardboard ash as a cement replacement, (3) curing process, and (4) evaluation of mechanical and absorption properties. Each stage was crucial for understanding the relationship between ash substitution and concrete performance in terms of strength and durability.

2.2. Stages of testing

2.2.1. Sample preparation

The selection and preparation of the concrete samples were critical to determining the total population of 104 samples. These were divided into two groups: 56 cylindrical specimens (6 by 12 inches) for testing water absorption speed and compressive strength, and 48 rectangular specimens (6 by 6 by 20 inches) for testing flexural strength. These groups allowed a comprehensive evaluation of how cardboard ash influences the main physical and mechanical properties of concrete.

2.2.2. Variable incorporation of ash

The concrete samples were evaluated under three experimental conditions: with 2.5%, 5%, and 7.5% cardboard ash as a cement substitute. The test objects were designed to measure three fundamental properties of concrete: compressive strength, flexural resistance, and water absorption. These were selected as key indicators of concrete performance when using cardboard ash as a partial cement substitute. Four experimental groups were established: three with varying proportions of cardboard ash and a control group without ash, as shown in Table 1. These proportions replaced the cement by weight to assess how cardboard ash affects the mechanical and physical properties of concrete.

Table 1. Coding and sample proportions.

Experimental groups	Proportions
GE0	Standard concrete
GE1	2.5% Cardboard ash
GE2	5.0% Cardboard ash
GE3	7.5% Cardboard ash

2.2.3. Curing process

Sample processing and sample preparation for fresh concrete samples taken in the field were conducted according to ASTM C31 (2024); sawn samples taken from cured material were tested according to ASTM C42 (2020); and samples made in the laboratory were evaluated following ASTM C192 (2024).

The samples were cured under standard conditions of temperature (23 ± 2 °C) and humidity (95 ± 2%) for 7, 14 and 28 days, as specified by ASTM standards. For the absorption test, the procedure of ASTM C1585 was used, while the compressive and flexural strength tests were performed according to ASTM C39 and ASTM C78, respectively.

2.2.4. Absorption test speed

ASTM C1585 (2020) states that water absorption in concrete depends on several factors, with the moisture state at the time of testing being one of the most important. The objective is to evaluate the vulnerability of unsaturated concrete to water penetration, noting that the absorption speed differs between the surface and the interior of the specimen due to less intensive curing and more extreme environmental conditions in the outer layer.

The procedure begins, after 28 days of curing, with the drilling of a concrete core that is cut transversely into 50 mm fragments. The two central sections are selected to ensure a representative sample, allowing evaluation of the absorption at various distances from the exposed surface. The fragments are placed in a desiccator at 50 °C, using a saturated solution of potassium bromide (20 g) and distilled water (25 g) to control the relative humidity without bringing the cores into direct contact with the solution. After three days, the samples are stored in waterproof bags to equilibrate their internal humidity and, after 15 days, they are ready for testing. It is important that the cores remain wrapped in waterproof material, except on the side exposed to water, simulating controlled natural conditions.

2.2.5. Compressive strength test

ASTM C39 (2024) establishes the procedure for performing compression tests on cylindrical concrete cores. For this test, cores were selected at curing ages of 7, 14 and 28 days. Once the required curing time was reached, the samples were subjected to compression testing using a properly calibrated hydraulic press. During the test, loads were applied continuously and at a constant speed of 5 and 15 MPa/s, until the specimen failed. Both the type of failure and the maximum resistance reached were recorded. The results obtained in kg/cm^2 were analyzed and compared with a reference sample, as well as with the minimum strength and quality values established by C39.

2.2.6. Flexural strength test

ASTM C78 (2022) establishes a procedure for flexural testing of concrete on rectangular specimens, using a calibrated "third point" hydraulic flexural breaking press. The specimen was in the shape of a 6-inch by 6-inch beam with a length of 20 inches. A protocol was followed, including correct specimen orientation and application of a preload to ensure gap-free contact. The test was performed automatically in a controlled system, which improves consistency and reduces the risk of impact compared to manual methods. During the test, the load was applied at a constant rate corresponding to an increase in bending stress between 0.90 and 1.20 MPa/min until the specimen fractured in the middle third of its length, in the tension area or at the bottom, with continuous records of load and displacement expressed in kg/cm^2 and then compared with a standard specimen and with the minimum and maximum parameters determined by C78.

2.2.7. Cardboard ash processing

The discarded cardboard came from packaging used by various companies. These materials, having fulfilled their original purpose, were selected to align sustainability goals, promoting recycling and efficient waste management. This reuse of materials helps reduce landfill waste and introduces a potentially sustainable additive for concrete production.

In this study, the recycling of cardboard followed the guidelines of Legislative Decree No. 1278 (Ministry of the Environment, [MINAM, 2016]), which establishes the Law on Integrated Solid Waste Management. This law addresses aspects such as source segregation, selective collection, and proper treatment to optimize the process and ensure that recycled cardboard is safe and effective for reuse. The recycled cardboard was collected from various areas of the city of Cusco, Peru, with an emphasis on avoiding contamination with organic materials, chemicals, or oils, as these factors compromise the recycling process or degrade the quality of the recycled material. Cardboard that had been in contact with contaminants or oils was not recycled and was treated as special waste.

Although there is no specific standard for cardboard ash, the guidelines of ASTM C618 (2023), which sets standards for coal ashes and natural or calcined pozzolans in concrete, were followed. In this study, the ashes obtained from the controlled combustion of recycled cardboard met specific granulometry criteria, facilitating a homogeneous mix with cement and other concrete components. The low moisture content and appropriate specific density of the ash ensured easy handling and precise dosing in the concrete mixes, contributing to consistent quality.

2.2.8. Characteristics of cardboard ash

To obtain a fine powder, the recycled cardboard was subjected to a combustion process following the parameters indicated by Jarre et al. (2021). In this case, a temperature of 650 °C was applied at intervals of between 90 and 120 minutes. The results are detailed in Table 2, which includes the chemical, physical, and mechanical properties of the ashes obtained from the recycled cardboard.

Table 2. Compositions of cardboard ash.

Chemical properties	**Values (%)**
CaO	5.44
Al_2O_3	0.01
SiO_2	46.12
Fe_2O_3	9.96
MgO	4.09
Physical-mechanical properties	**Values**
Moisture content (%)	1.18
Loose unit weight (kg/m³)	1,203
Compacted unit weight (kg/m³)	1,326
Density (g/cm³)	2.76
Absorption (%)	2.9
Modulus of fineness	2.16

The chemical analysis revealed a composition of 5.44% calcium oxide (CaO), 0.01% aluminum oxide (Al_2O_3), 46.12% silicon dioxide (SiO_2), 9.96% iron (III) oxide (Fe_2O_3), and 4.09% magnesium oxide (MgO). These components, particularly silicon and iron oxides, are known for improving the durability and compressive strength of concrete, suggesting that the ashes have the potential to positively contribute to the overall performance of the material.

In physical and mechanical terms, the ash has a moisture content of 1.18%, a loose bulk density of 1,203 kg/m^3, a compacted bulk density of 1,326 kg/m^3, a density of 2.76 g/cm^3, an absorption speed of 2.90%, and a fineness modulus of 2.16. These characteristics suggest a low water retention capacity, considerable density, and fine grain size, which could influence its behavior as a partial cement substitute in concrete mixes.

2.2.9. Natural aggregates processing

The natural aggregates used in this study were obtained from the "Vicho" quarry, located in the department of Cusco (± 3400 meters above sea level), selected for its availability and convenient transport planning. The quarry was known for the high quality of its raw material, fully complying with the ASTM C33 (2023) specifications, ensuring optimal performance in concrete production.

The fine aggregates were free from impurities such as salts, alkalis, and organic matter, which could otherwise compromise the setting and strength of the concrete. Similarly, the coarse aggregates were clean, with minimal amounts of clay, organic particles, or fines that could negatively affect the adhesion of the cement. These aggregates met the strict standards for gradation, density, water absorption, and abrasion resistance, ensuring high performance in the concrete mix.

These standards ensured the reliability of all stages of the process, from the collection of natural aggregates and cardboard ash to the final stage of concrete processing.

2.2.10. Granulometry of aggregates

The granulometry test of fine and coarse aggregates, shown in Figure 1, was carried out following the ASTM C33 (2023) and ASTM C136 (2020) guidelines. The percentage of aggregates passing through different sieve sizes (in mm) for both types of aggregates shows adequate gradation according to ASTM specifications. This is crucial to ensure good workability, strength, and durability in the concrete mix, as proper gradation reduces voids and optimizes particle distribution.

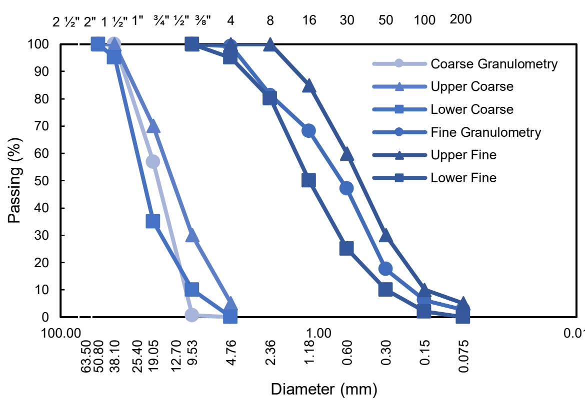


Figure 1. Granulometry of natural aggregates.

The gradation curves show an adequate distribution, with specific uniformity coefficients and a fineness modulus of 2.81, which ensures good concrete workability and reduces the amount of cement required. These values fall within the permitted limits, confirming that the aggregates used meet the requirements for high-quality concrete production. Furthermore, the proper gradation improves concrete workability and minimizes the amount of cement needed to achieve the desired strength.

2.2.11. Properties of aggregates

The tests performed on the natural aggregates, whose results are shown in Table 3, provide essential information about their physical and mechanical properties. These results were compared with ASTM standards ASTM C29 (2023), ASTM C127 (2024), ASTM C128 (2023), ASTM C131 (2020), and ASTM C566 (2019).

The recorded moisture content was 1.26% for fine aggregates and 2.95% for coarse aggregates, indicating appropriate levels for concrete production, which are generally below 3.0%. Maintaining appropriate moisture levels is crucial, as excess moisture can lead to unwanted expansion or contraction in the concrete, while low moisture levels can affect workability.

The loose and compacted bulk densities were 1,481 kg/m^3 and 1,551 kg/m^3 for fine aggregate, and 1,543 kg/m^3 and 1,619 kg/m^3 for coarse aggregate, within the typical ranges of 1,400–1,600 kg/m^3 and 1,500–1,700 kg/m^3, respectively. The specific gravity was 2.55 g/cm^3 for fine aggregate and 2.63g/cm^3 for coarse aggregate, both within the standard range of 2.4–2.9 g/cm^3. The absorption was 1.52% for fine aggregate and 1.0% for coarse aggregate, within the acceptable values (0.1–2% for fines and 0.1–3% for coarse). The fineness modulus of fine aggregate was 2.81, within the typical range of 2.3 to 3.1. The nominal maximum size of the coarse aggregate was 19.05 mm. Finally, the abrasion wear was 14.78%, indicating adequate resistance, as values below 30% are considered acceptable. In general, these values comply with ASTM specifications, ensuring that natural aggregates are suitable for use in concrete mixes.

Table 3. Physical-mechanical properties of aggregates.

Tests	Coarse	Fine
Specific gravity (g/cm^3)	2.63	2.55
Moisture content (%)	2.95	1.26
Absorption (%)	1.00	1.52
Modulus of fineness (%)	—	2.81
Loose unit weight (kg/m^3)	1,543	1,481
Compacted unit weight (kg/m^3)	1,619	1,551
Nominal maximum size (mm)	19.05	—
Abrasion wear (%)	14.78	—

2.3. Mix design

The mix design was conducted according to the ACI PRC-211.1 (2022) guidelines, aiming to ensure that the concrete mixes produced meet the necessary strength and durability requirements for severe environments (F1). Table 4 shows the quantities of materials used in wet weight proportions for one cubic meter.

Table 4. Mix design in wet weight proportions.

Components	GE0 (kg)	GE1 (kg)	GE2 (kg)	GE3 (kg)
Cement	448.15	436.95	425.75	414.54
Cardboard Ash	0.0	11.20	22.41	33.61
Water (L)	164.72	164.70	164.69	164.67
Aimix 400	0.22	0.23	0.24	0.24
Euco 37	3.59	3.67	3.76	3.85
Accelguard 100	2.69	2.76	2.82	2.89
Coarse	899.80	890.86	884.63	878.40
Fine	702.09	695.12	690.25	685.39
Slump (mm)	90.68	92.20	94.74	89.66

Specific mix proportions, designed to incorporate different percentages of cardboard ash, were developed to optimize strength while improving the sustainability of the concrete. Four mix designs were created to achieve a specified strength of 280 kg/cm^2, using cardboard ash in proportions of GE1, GE2, and GE3 as a partial substitute for cement. The cement used had a specific gravity of 2.80 g/cm^3, a slump of 76.2 to 101.6 mm, a total air content of 5%, and a water-cement ratio of 0.41.

A progressive decrease in the amount of cement was observed as the controlled percentages of cardboard ash increased in groups GE1, GE2, and GE3, with reductions of 2.56%, 5.26%, and 8.11%, respectively. These groups replaced variable amounts of cement, incorporating 3.28 kg, 6.57 kg, and 9.85 kg of ash into the mix. This significant reduction in cement content had a direct impact on the physical and mechanical properties of the concrete, enhancing sustainability while maintaining the necessary strength and workability.

Regarding the air-entraining additive (Aimix 400), the water-reducing agent (Euco 37), and the set accelerator (Accelguard 100), a slight increase in their amounts was observed as the content of ash increased, likely to counteract changes in workability and the properties of workability, ensuring cohesion and manageability of the mix.

Although the variations were minimal, both coarse and fine aggregates exhibited slight reductions in weight as the percentage of ash increased. This adjustment was necessary to balance the volumetric properties and density of the mix, which in turn positively impacted the final strength and durability of the concrete.

The slump test, also known as the Abrams cone test, was conducted following the ASTM C143 (2020) guidelines. Three measurements were taken for each mix design, and an average was calculated for each mixture. Group GE0 recorded a slump of 90.68 mm, while groups GE1 and GE2 showed slight increases, with values of 92.20 and 94.74 mm, respectively, indicating improved workability with the inclusion of controlled proportions of cardboard ash. Group GE3 showed a decrease to 89.66 mm, falling within the specified slump range of 76.2 to 101.6 mm. These results suggest that maintaining equal or lower proportions of cardboard ash in the GE3 mix does not negatively affect the consistency of the mix, ensuring the workability required for construction.

3. Results

Extensive tests were conducted on the concrete after 7, 14, and 28 days of curing to evaluate various physical and mechanical properties, including slump, water absorption speed, and mechanical behavior under compression and flexural loads.

3.1. Water absorption speed

This method was used to measure the water absorption speed in hydraulic concrete mixes, evaluating the increase in mass of a specimen over time, while only one of its surfaces was exposed to water. The procedure was carried out in accordance with ASTM C1585, as shown in Figure 2.

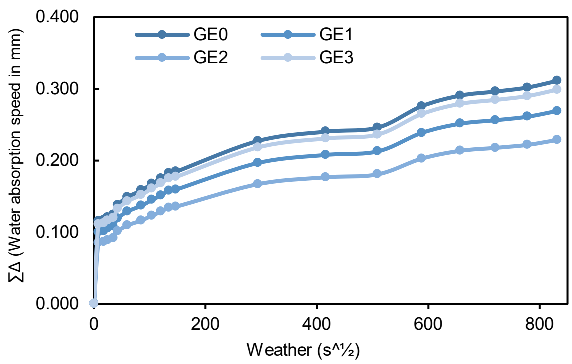


Figure 2. Behavior of the water absorption speed in concrete.

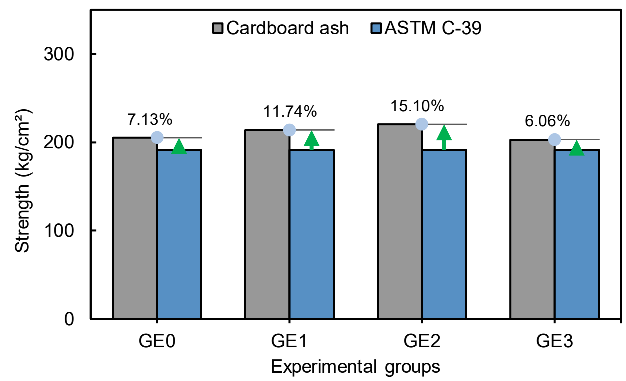
The experimental groups show a gradual increase in the water absorption speed (∑Δ) with a time of 831.38 s^½. Group GE0 reached 0.311 mm, indicating a porous structure that facilitates water absorption, a characteristic observed in ash-free mixes. In contrast, group GE1 shows a reduction in ∑Δ compared to group GE0, with a value of 0.269 mm, indicating improved impermeability due to the ashes acting as a porosity-reducing agent. Group GE2 shows an additional reduction in ∑Δ, reaching 0.229 mm. This mix exhibits the lowest ∑Δ among all evaluated mixes, indicating that this proportion of ash is the most effective for improving the impermeability of the concrete. However, group GE3 registers an ∑Δ of 0.299 mm. Although this is still better than group GE0, the water absorption is higher in comparison to GE1 and GE2.

Another perspective on the results shows that during the initial exposure stages, capillary absorption was similar for all types of concrete. After 120 s^½, a slight decrease in absorption was observed in the concrete with ash, particularly in group GE2, which exhibited the lowest capillary absorption over time. In the intermediate stage (297.94 to 415.69 s^½), all concrete mixes displayed an increase in absorption, but groups GE1 and GE2 maintained lower absorption compared to the standard concrete (GE0). At the end of the test (831.38 s^½), group GE3 showed an increase in capillary absorption, although it remained below group GE0. This suggests that excessive content of ash could negatively affect the impermeability of the concrete. In both perspectives, the water absorption results indicate that the inclusion of cardboard ash improves the impermeability of the concrete.

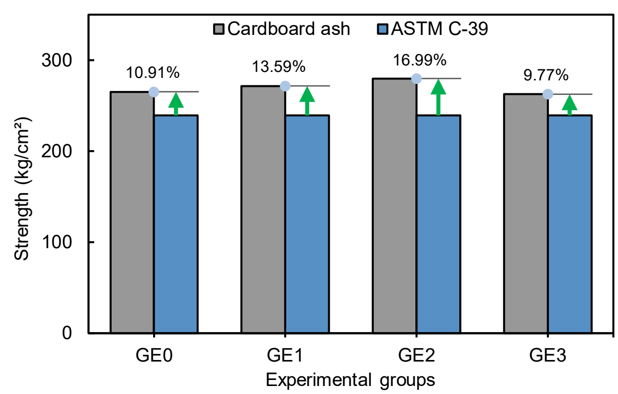
3.2. Compressive strength

The compressive strength results demonstrated the superior performance of the mixes with cardboard ash compared to GE0 and the ASTM reference values: 191.48 kg/cm^2 at 7 days, 239.22 kg/cm^2 at 14 days, and 280 kg/cm^2 at 28 days, as shown in Figure 3.

The results obtained at 7 days show that group GE0 reached a compressive strength of 205.14 kg/cm^2, exceeding the ASTM reference value by 7.13%. The mixes containing cardboard ash performed even better, with group GE2 achieving a strength of 220.39 kg/cm^2, representing an increase of 15.10% over the ASTM standard and 7.97% above group GE0. At 14 days, all mixes continued to show improvements in strength, with group GE2 standing out, achieving a strength of 279.88 kg/cm^2, which is 16.99% higher than the ASTM standard and 6.08% higher than group GE0, which recorded 265.31 kg/cm^2. Finally, at 28 days, all mixes surpassed the required strength (280 kg/cm^2). Group GE2 achieved a strength of 331.56 kg/cm^2, representing an increase of 18.41% over the ASTM standard and 5.75% higher than group GE0, which reached 315.44 kg/cm^2, an increase of 12.66%.



(a)



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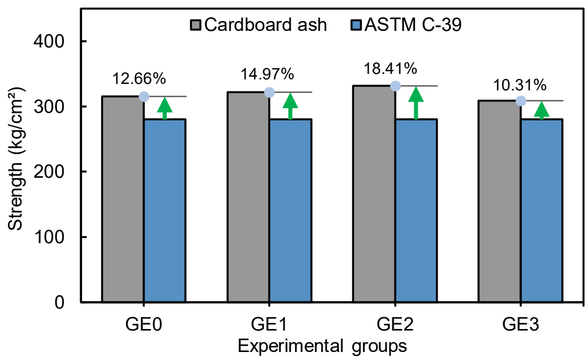


(c)

Figure 3. Compressive strength of concrete:
(A): 7 days; (B): 14 days; (C): 28 days.

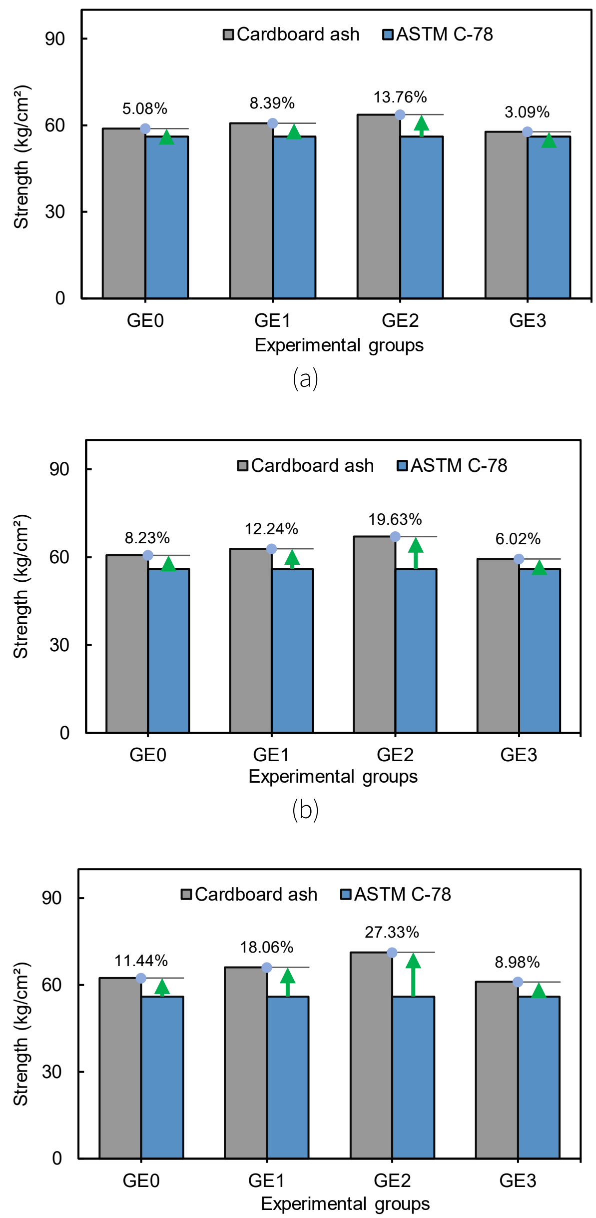
In this context, group GE2 demonstrated the best performance across all evaluated periods, with increases of 15.10% in 7 days, 16.99% at 14 days, and 18.41% at 28 days compared to the ASTM C39 reference values of 7.97%, 6.08%, and 5.75% more than group GE0. These results indicate that cardboard ash, when used in optimal quantities as in mixed GE2, improves the compressive strength of concrete, making it a promising option as a partial substitute for cement, especially in environments with aggressive conditions.

3.3. Flexural strength

The flexural strength test of the concrete provided an analysis detailing the performance of different mixes with cardboard ash compared to group GE0 and the reference values of ASTM C78, which establishes a minimum of 28 kg/cm² for 10% and a maximum of 56 kg/cm² for 20%. Figure 4 shows the results at three-time intervals: 7, 14, and 28 days.

Over the 7 days, group GE2 achieved an increase of 13.76% in flexural strength, while GE1 showed an increase of 8.39%. Although group GE3 also exceeded the standard, its performance was lower compared to group GE0 (5.08%), with a modest increase of 3.09%. On 14 days, both GE1 and GE2 continued to show significant improvements, with increases of 19.63% and 12.24%, respectively, above the ASTM standards and group GE0. Group GE3, while showing an increase of 6.02%, did not surpass group GE0, which reached 8.23%. Finally, at 28 days, the positive behavior of the mixes with cardboard ash was confirmed, particularly in group GE2, which achieved an increase of 27.33% over the ASTM reference value and surpassed group GE0 by 15.89%. Groups GE1 and GE3 also showed improvements, although GE3 experienced a slight decrease of 2.46% compared to GE0.

The analysis of the data obtained at 7, 14, and 28 days clearly shows how cardboard ashes, when used as a partial substitute for cement in concrete mixes, significantly improve flexural strength compared to group GE0 and the reference values established by ASTM C78 (56 kg/cm²). Group GE2, with the highest optimal concentration of ashes, demonstrated exceptional performance across all evaluation periods, achieving considerable increases. In this regard, the results indicate that cardboard ashes have a positive effect on the flexural strength of concrete, especially at the concentrations found in group GE2. This establishes cardboard ashes as a promising additive for improving the properties of concrete in applications in severe climate environments.



(c)

Figure 4. Flexural strength of concrete:
(A): 7 days; (B): 14 days; (C): 28 days.

3.4. Statistical analysis

Figure 5 shows the results of the ANOVA statistical analysis, confirming that the variations observed in the water absorption speed and compressive and flexural strength are highly significant and not attributable to random variation.

The water absorption speed shows moderate capacity (∑Δ = 4.884E-02), which is crucial for the concrete's durability. A lower absorption speed suggests improved density and reduced porosity, enhancing resistance to external agents. For compressive strength (*f'c*), a p-value of 1.564E-05 was observed at 28 days, reflecting the significant strengthening of the material over time due to the hydration process. The flexural strength (*Mr.*) also showed significance, with a p-value of 1.684E-05 at 28 days. All p-values were below the alpha significance level (0.05), indicating extremely high statistical significance in the results across all evaluated periods.

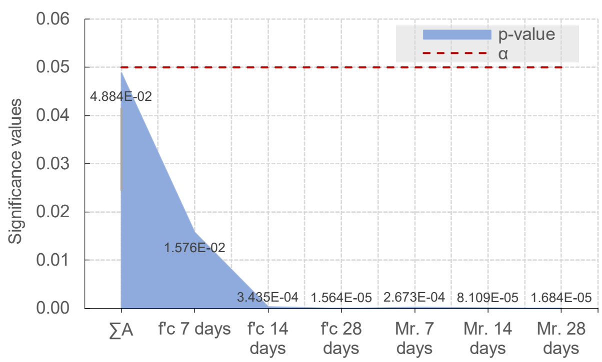


Figure 5. Statistical Analysis — ANOVA.

The p-values obtained from the ANOVA confirm that the observed improvements in water absorption, compressive strength, and flexural strength due to the addition of cardboard ash are statistically significant, indicating that these results are unlikely due to random variation. The statistical analysis supports the hypothesis that the partial substitution of cement with recycled cardboard ash improves the mechanical properties of concrete, particularly in terms of compressive and flexural strength, as confirmed by the statistically significant p-value.

4. Discussion

Regarding the water absorption speed, the results showed a value of 0.229 mm at 831.38 s^½ with the incorporation of 5% cardboard ash, indicating a reduction in the absorption speed compared to conventional concrete. In addition, significant improvements in mechanical strength were observed, with maximum increases of 15.10%, 16.99% and 18.41% in compressive strength, and 13.76%, 19.63% and 27.33% in flexural strength. These results comply with the parameters established by ASTM C39 and C78. Thus, the greatest improvement in concrete properties was achieved with the addition of 5% cardboard ash.

Furthermore, statistical analyses showed significant differences between the different additions of cardboard ash in the physical and mechanical tests, with a p-value below the significance threshold (α=0.05). This underlines the potential of cardboard ash to improve the properties of concrete, suggesting its viability as an alternative material in the production of this material.

The results obtained in this study are consistent with those of Carpio and Muñiz (2024), who also investigated the effect of the addition of cardboard ash (CC) in hydraulic concrete. In their work, they evaluated concentrations of 1.5%, 3%, 4.5%, and 6% of CC, and found improvements in concrete properties. Water absorption reached 0.061 g/s and permeability was 297.09 g/m². In terms of strength, compressive strength reached 323.34 kg/cm² and flexural strength was 35.76 kg/cm² at 28 days of curing. According to their findings, the best improvement was achieved with a 3% addition of cardboard ash, which reinforces the results obtained in this study and suggests the effectiveness of cardboard ash in improving concrete properties.

Similarly, Haigh et al. (2023) investigated the use of Kraft fiber from recycled cardboard to evaluate its impact on the water permeability of new composites. Through absorption and immersion tests, a reduction in chloride ion transfer was observed in all fiber composites, even after one year of exposure. The composites were subjected to wet-dry aging cycles and then evaluated in terms of compressive and tensile strength at various time intervals. The compressive strength of all samples peaked between 60 and 80 cycles per day. On the other hand, the fiber matrix-modified composites exhibited a tensile strength of 2.5 MPa after being subjected to 100 cycles per day, while the control showed a strength of 2.7 MPa. These results demonstrate the potential of cardboard fibers to improve the durability and strength of composites under adverse conditions.

Finally, the study by Alyami et al. (2023) investigated the use of paper sludge ash (WPSA) as a partial cement substitute, evaluating percentages of 5%, 10%, 15%, 20% and 25% in the total cement mass. The results indicated that the inclusion of WPSA at 25% produced the best properties in terms of transport, achieving the lowest water absorption (17.4%) and the lowest porosity (37.75%). In terms of mechanical properties, it was observed that 15% of WPSA offered the highest strengths, with a compressive strength of 11.2 MPa and a flexural strength of 2.61 MPa. These findings highlight the potential of paper sludge ash as a sustainable and effective material for improving concrete properties.

In this context, the materials used by the authors are closely related to cardboard ash. Although different percentages may be used compared to the present study, it is essential to highlight that the use of alternative materials in construction has become a growing trend aimed at mitigating environmental impact. These studies demonstrate how recycled by-products, such as cardboard ash, paper sludge ash, and used cardboard fibers, can not only partially replace cement but also improve various properties of concrete, such as water absorption resistance, and compressive and flexural strength, while contributing to the sustainability of the construction sector.

5. Conclusions

The study focused on analyzing the effect of cardboard ash on the properties of concrete when cement is partially substituted, allowing for an understanding of the behavior of concrete in both its fresh and hardened states. Based on the results obtained, the article concludes:

This study has demonstrated that the use of recycled cardboard ash as a partial substitute for cement significantly improves the physical and mechanical properties of concrete. The optimal proportion identified was 5%, which allows for an adequate balance between durability, compressive strength, and flexural strength, as well as a significant reduction in water absorption.

The use of this industrial byproduct optimizes the properties of concrete and provides a more sustainable alternative by reducing cement consumption. This research determines that recycled cardboard ash contributes to more ecological and efficient construction, promoting a circular economy through waste reuse.

The inclusion of recycled cardboard ash enhances the technical properties of concrete while reducing the environmental impact of the construction industry, aligning with various Sustainable Development Goals (SDGs). It promotes responsible production (SDG 12), fosters innovation in sustainable infrastructure (SDG 9), supports the creation of sustainable cities (SDG 11), and reduces the carbon footprint (SDG 13). This research presents a sustainable and efficient alternative with the potential to transform practices in the construction industry.

The results of this study confirm the hypothesis, demonstrating that replacing cement with 5% recycled cardboard ash leads to significant improvements in the mechanical properties of concrete while reducing its carbon footprint. Although this study demonstrates the positive impact of ash as a cement substitute, its scope is limited by the environmental conditions tested. Future research should explore the long-term durability of concrete mixes in different climates, as well as their compatibility with other sustainable materials. In addition, the economic feasibility and large-scale application of this material in construction should be evaluated.

Conflict of interest

The authors do not have any type of conflict of interest to declare.

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